

**USARIEM TECHNICAL REPORT T06-03**

**INITIAL CAPABILITY DECISION AID (ICDA) THERMAL PREDICTION MODEL  
AND ITS VALIDATION**

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The ICDA (Initial Capability Decision Aid) is a heat stress prediction model recently developed for monitoring the physiological status of Soldiers. ICDA utilizes real time input of metabolic activity derived from heart rate and air temperature. The model validation was conducted using data from three laboratory studies with varied environments (i.e., 27°C/75%RH; 49°C/18%; 35°C/45%), clothing configurations and heat acclimation status. Subjects walked on a treadmill at ~270-628 W for up to 180 min, depending upon study conditions. Root Mean Square Deviation (RMSD) between measured and predicted core temperature (Tcr) ranged between  $\pm 0.11$  and  $\pm 0.50$ °C for these studies. The model predicted measured values of Tcr within one standard deviation, when environmental conditions were less stressful. Errors of estimates were larger with small sample size (N<5). The ICDA predictions of skin temperature were less accurate than those of Tcr. ICDA predictions of sweat rates (SR) were more accurate when environmental conditions were, in terms of heat stress, less extreme. However, for encapsulated subjects, working in a 35°C/45%RH environment, the results for predictions of SR were mixed. This model shows promising prediction of thermal status, particularly Tcr, of Soldiers during heat stress. This non-invasive model is convenient for health assessment of Soldiers required to perform different tasks for long hours.

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Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR70-25 and USAMRMC Regulation 70-25 on the Use of Volunteers in Research. For protection of human subjects, the investigator(s) adhered to policies of applicable Federal Law CFR 46.

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## EXECUTIVE SUMMARY

The ICDA (Initial Capability Decision Aid) is a heat stress prediction model recently developed for monitoring the physiological status of Soldiers. The ICDA is an abridged version of the USARIEM human thermal physiological simulation computer model SCENARIO-J (Kraning and Gonzalez., 1997) and the Gagge model (Gagge et al., 1986). ICDA utilizes real time input of metabolic activity (M) derived from heart rate (HR) and air temperature. By using HR to estimate M, Soldiers required to perform multiple tasks over extended time periods can be monitored with non-invasive sensors which are both convenient to place and comfortable to wear. This study compares ICDA predictions of core temperature ( $T_{cr}$ ), skin temperature ( $T_{sk}$ ), and sweat rates (SR) with laboratory measured values.

The model validation was conducted using data from three laboratory studies with varied environments (i.e., 27°C/75%RH; 49°C/18%; 35°C/45%), clothing configurations and heat acclimation status. Subjects walked on a treadmill at ~270-628 W for up to 180 min, depending upon study conditions.  $T_{cr}$  rise was restricted to <39.5°C. Individual anthropometrics, physiological and environmental time series data were collected in each study. Root Mean Square Deviation (RMSD) was utilized to examine the difference between laboratory measurements and ICDA predictions of  $T_{cr}$  and  $T_{sk}$  across time. In addition, predicted SR was compared to the measured SR where available.

RSMD of  $T_{cr}$  ranged between  $\pm 0.11$  and  $\pm 0.50^\circ\text{C}$  for these studies. The model predicted measured values of  $T_{cr}$  within one standard deviation, when environmental conditions were less stressful. Errors of estimates were larger with small sample size ( $N < 5$ ). The ICDA predictions of  $T_{sk}$  were less accurate than those of  $T_{cr}$ . Generally, model predictions of  $T_{sk}$  were more difficult than  $T_{cr}$  because measured  $T_{sk}$  varied by skin location, clothing, environmental, and operational conditions. ICDA predictions of SR were more accurate when environmental conditions were, in terms of heat stress, less extreme. However, for encapsulated subjects, working in a 35°C/45%RH environment, the results for predictions of SR were mixed.

Predictions of thermal status of Soldiers during heat stress, particularly for  $T_{cr}$ , using this simplified model, are promising. To improve predictions of  $T_{sk}$ , the existing data bases should be evaluated to determine which  $T_{sk}$  measurement site best represents the combined impact of individual variability, clothing, environment, and operations on  $T_{sk}$ , and is therefore, the best site to use for model development and validation of  $T_{sk}$  predictions. Similarly, for SR predictions, the trends of individual SR patterns need to be carefully evaluated to further refine this model. Lastly, it is recommended that ICDA be applied to real time situations in both laboratory and field training exercises for future  $T_{cr}$  sensitivity analysis, and further model development.



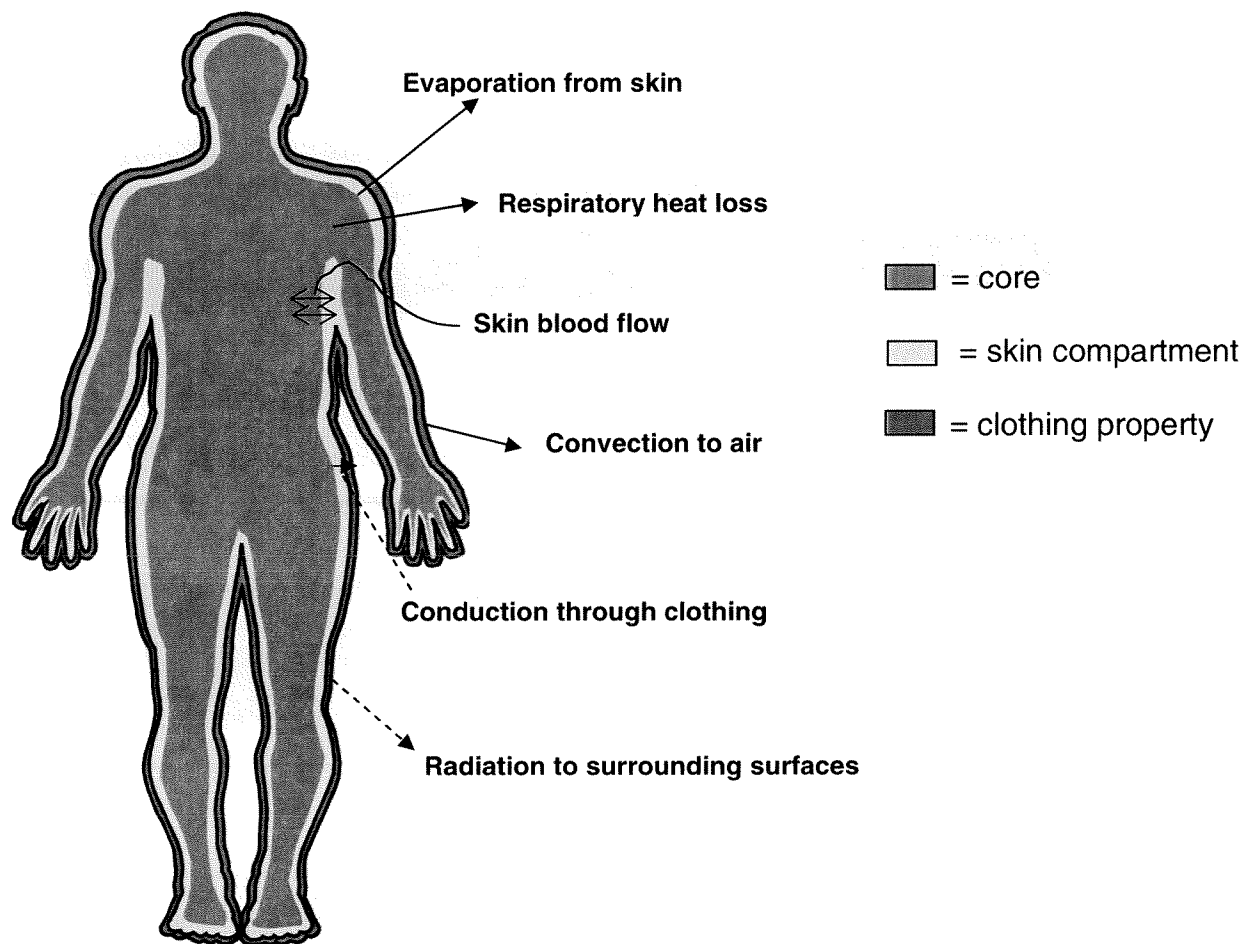
## INTRODUCTION

The ICDA (Initial Capability Decision Aid) model is a heat stress prediction model recently developed for monitoring the physiological status of Warfighters. It is a basic and abridged model derived from elements of the USARIEM human thermal physiological simulation computer model, SCENARIO-J (Kraning and Gonzalez, 1997), and the Gagge Model (Gagge et al., 1986). The model can be loaded with anthropological characteristics of an individual (i.e., height, weight, and clothing), group means or use default population values. Real-time inputs of measured HR and local weather (e.g., temperatures, wind, relative humidity, estimates of radiant load) are used by the computer model to make real-time predictions and estimates of subjects' physiological status or other physiological parameters.

A main purpose for constructing this model was to predict time estimates of the internal body temperature ( $T_{cr}$ ), sweat rates (SR), and hydration status of Soldiers and Warfighters in a battlefield situation. For instance,  $T_{cr}$  is the traditional and common physiological parameter for heat strain assessment as it reliably indicates impending injury (Amos et al., 2000; Pandolf and Goldman 1978). However, measuring  $T_{cr}$  is invasive and may be impractical for real time monitoring of Soldiers engaged in long hours of various multiple and unpredictable tasks in widely disbursed hot field environment. Although obtaining "true" values of many parameters from environmental, physiological and operational conditions are desirable and increases the model's accuracy to assess Soldiers' status, alternatives for the worst case scenario (e.g., losing signals from sensor devices, wrong calibration, conflicts between sensors, etc) still need to be considered. For these reasons, ICDA was developed to predict physiological responses to battlefield situations from a minimum number of non-invasive inputs.

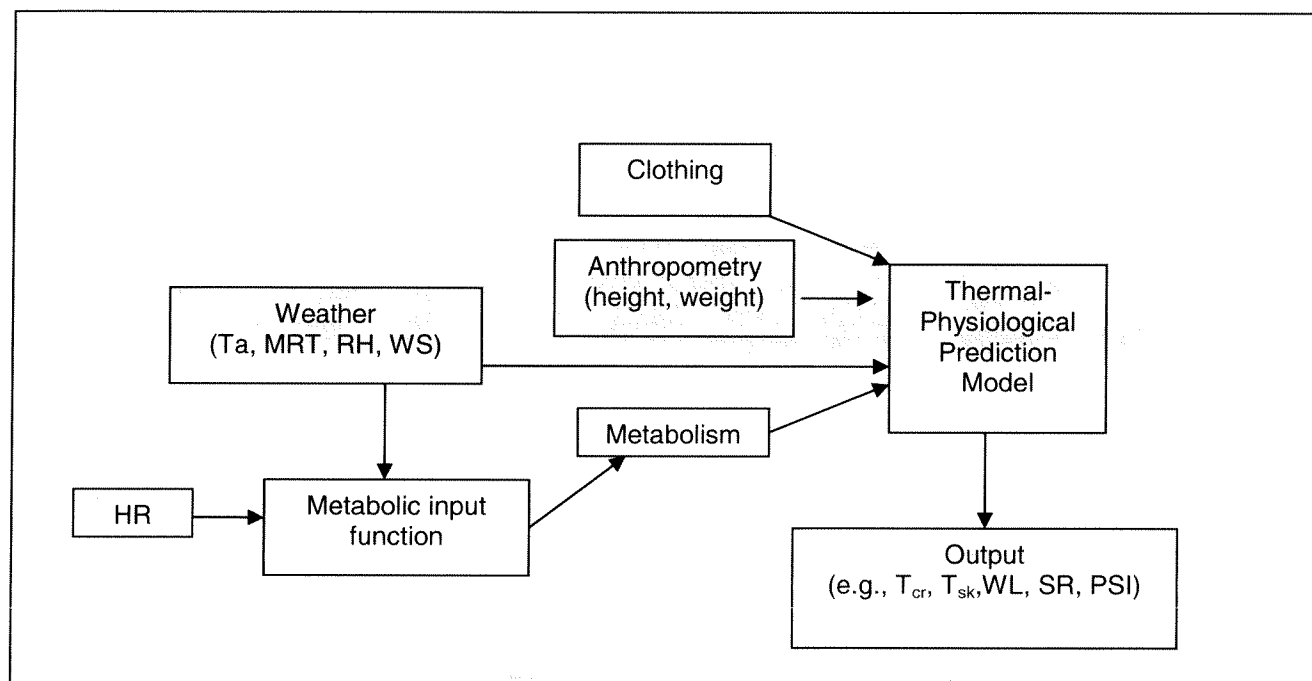
The thermal physiology of the ICDA model is represented schematically in Figure 1, where the human is modeled as two physiological compartments (core and skin) surrounded by a passive clothing compartment. Within a compartment the properties are uniform: i.e., everywhere in core at time  $t$ ,  $T_{cr}$  has the same value. All metabolic heat production ( $M$ ) occurs in the core. Some heat is lost directly from the core to the environment by respiration; all of the other heat from the core is transferred to the skin by conduction or convection with skin blood flow. The primary method used to regulate  $T_{cr}$  is achieved by controlling blood flow.

Figure 1. Schematic of core, skin and clothing compartments



The basic ICDA operational structure is summarized in Figure 2. The outline identifies the simulation routines used to predict an individual's  $T_{cr}$ , sweat rate, accumulated water loss (WL), skin temperature ( $T_{sk}$ ), metabolism, and a thermoregulatory strain indicator quantified by the physiological strain index (PSI) (Moran et al., 1988).

Figure 2. Basic operational structure of ICDA



Recent reports from wars in Iraq and Afghanistan indicate that faster access to medical/surgical care and identifying evacuation situations would save more Soldiers' lives (Bilski et al., 2003; Gawande, 2004). The current strategies to shorten the time lag between injury and treatment is to position a small surgical care unit near the battlefield (Bilski et al., 2003). The model can contribute this effort by forecasting both real-time and future probabilities of Soldiers' health status by notifying unit medical personnel and command elements on the battlefields. The ICDA will also provide a longitudinal projection of SR, which can be used to predict Soldiers' dehydration status and water requirements. SR predictions are important for both logistics and for Soldiers to assess unit and individual water requirements (Montain et al., 2005). Thus, logistics personnel can plan for water delivery to meet the projected demand and the associated cost, and Soldiers can sustain their physical and cognitive performance by preventing from dehydration.

This study described the basic concept of the ICDA model, and presents an evaluation of model performance with a focus on T<sub>cr</sub>, T<sub>sk</sub> and SR predictions using available data from military heat studies. Comparisons of measured physiological data with the model predictions provide the analytical basis needed to characterize model performance and, if necessary, identify further improvements of the model.

## METHODS

### ICDA MODEL

The ICDA model as described in the Introduction represents the human by two active physiological compartments (core and skin) surrounded by a passive clothing compartment. The model was designed for military personnel, who routinely are heat acclimatized and have normal or low levels of body fat relative to the general population.

**Metabolism (M):** The source of heat production in the core compartment is metabolic activity. Thus, M is an important parameter for estimating  $T_{cr}$  and  $T_{sk}$ . Real time estimates of M for input into the ICDA model are derived from the Soldiers' measured HR and environmental temperatures (Berglund, 1977) using the following equation:

$$M = [0.68 + 4.69 \cdot (HR_{ratio} - 1) - 0.052 \cdot (HR_{ratio} - 1) \cdot (T_a - 20)] \cdot 58.1 \cdot Adu \text{ [W]} \quad (1)$$

where  $HR_{ratio}$  = observed HR given at the time divided by the resting HR of the individual, and  $T_a$  = ambient temperature in °C. Adu is the body surface area. The basis for Equation 1 is that M as HR increases for a given task at an elevated  $T_a$ . The heart pumps blood to transport oxygen to the cells to support the metabolic effort and to exchange heat at the skin in order to cool the core. This increased HR to the skin is a non-metabolic activity. The metabolic adjustment for  $T_a$  in Equation 1 corrects HR for the non-metabolic cooling function of skin blood flow.

This equation is applicable for the conditions including  $20^\circ\text{C} \leq T_a \leq 40^\circ\text{C}$ ,  $1.2 \leq HR_{ratio} \leq 2.1$ , wind speed  $\approx 1.25 \text{ ms}^{-1}$ , dew point temperature  $\leq 20^\circ\text{C}$ , and an intrinsic clothing insulation of about 0.6-0.7clo (i.e. that of a BDU). Within these limits, a good relationship exists between HR and  $O_2$  uptakes for different work rates in laboratory studies (Berglund, 1977). HR is non-invasive and convenient to measure compared to  $T_{cr}$ , particularly for long-duration duty assignments.

**Heat balance:** A heat balance analysis of the core compartment yields,

$$M/Adu = q_{res} + q_k + q_{skbf} + (W_c/Adu) \cdot c_{bt} \cdot (dT_{cr}/dt) \quad [\text{W/m}^2] \quad (2)$$

where

Adu = the body surface area

$q_{res}$  = respiratory heat loss

Specific heat of body tissue ( $c_{bt}$ ) is constant as  $.97 \text{ W} \cdot \text{h}/^\circ\text{C} \cdot \text{kg}$ , and

$W_c$  = the weight (kg) of core.

Passive heat conduction ( $q_k$ ) from core to the skin  $= k \cdot (T_{cr} - T_{sk})$

Conductance ( $k$ ) of tissue between core and skin  $= 5.28 \text{ W}/(^\circ\text{C} \cdot \text{m}^2)$ .

the heat transported by blood flow ( $q_{skbf}$ ) to the skin  $= Sk_{bf} \cdot c_{pb} \cdot (T_{cr} - T_{sk})$ ,

Where specific heat of blood ( $c_{pb}$ )  $= 1.163 \text{ W} \cdot \text{h}/(^\circ\text{C})$ .

Skin blood flow (Skbf) =  $[Skbf_n + C_{dil} \cdot (T_{cr} - T_{cset})] / (1 + C_{str} \cdot (T_{skset} - T_{sk}))$   
 where The vasodilation coefficient ( $C_{dil}$ ) =  $50 \text{ L}/(\text{h} \cdot \text{m}^2 \cdot ^\circ\text{C})$   
 The neutral  $Skbf_n$  =  $6.3 \text{ L}/(\text{h} \cdot \text{m}^2)$ ,  
 vasoconstriction coefficient,  $C_{str}$ , =  $0.5 \text{ } ^\circ\text{C}^{-1}$ .  
 $T_{cset} = 36.8^\circ\text{C}$ , and  $T_{skset} = 33.7^\circ\text{C}$ .

Skbf is modeled proportional to changes in  $T_{cr}$  and  $T_{sk}$  from set point temperatures ( $T_{crset}$ ,  $T_{skset}$ ). The maximum and minimum Skbf limits were set to 90 and 2 L/min, respectively.

The rate of  $T_{cr}$  change ( $T_{cr}/dt$ ) found by rearranging Equation 2:

$$T_{cr}/dt = (M/Adu - q_{res} - q_k - q_{skbf}) / (Wc \cdot c_{bt}/Adu), \quad (3)$$

can be step-wise integrated to find the next  $T_{cr}$  ( $T_{cr2}$ ) after time step ( $\Delta t$ ):

$$T_{cr2} = T_{cr1} + [dT_{cr}/dt]_1 \Delta t \quad (4)$$

In a similar fashion, the energy balances of the skin compartment can result in:

$$q_{skbf} + q_k = q_{dry} + q_{evap} + W_{sk}/Adu \cdot c_{bt} \cdot (dT_{sk}/dt) \quad (5)$$

where  $q_{skbf}$  and  $q_k$  represent conduction and blood flows from the core to skin. Dry heat flow from the skin to the clothing compartment is  $q_{dry}$ , and  $q_{evap}$  is the evaporative heat losses from the skin.  $W_{sk}$  represents the weight (kg) of skin.

As with the core compartment, the rate of change of skin temperature in the compartment determined from the energy balance can be stepwise integrated to find the compartment's skin temperature at time  $t + \Delta t$ .

**Heat transfer:** The model of heat exchange between the human skin surface, clothing and environment is defined by functions for effective air movement, resistance to heat flow by radiation and convection, and the resistance to evaporative heat transfer (Kraning and Gonzalez, 1991). This dry heat loss (Dry) was determined by:

$$\text{Dry} = (T_{sk} - T_o) / (R_{clt}) \quad [\text{W}/\text{m}^2] \quad (6)$$

where  $R_{clt}$  is the total dry thermal resistance between skin and the environment and  $T_o$  is the operative temperature.  $R_{clt}$  values used in the ICDA validation process are from thermal manikin measurements for the specific clothing ensembles used in this model.  $T_o$  is defined as:

$$T_o = (hc \cdot T_a + hr \cdot T_r) / (hc + hr) \quad [^\circ\text{C}] \quad (7)$$

where  $T_a$  and  $T_r$  in Equation 7 represent air and radiant temperatures, respectively. The  $hr$  and  $hc$  terms are the coefficients of radiant and convective heat transfer, defined by the following two equations:

$$hr = 4\sigma \cdot (A_r/A_D) \cdot \left[ \frac{T_{cl} + T_o}{2} + 273 \right]^3 \quad [W/(\text{°C} \cdot \text{m}^2)] \quad (8)$$

$$hc = 8.6 \cdot V^{.53} \quad [W/(\text{°C} \cdot \text{m}^2)] \quad (9)$$

where  $\sigma$  is the Stefan-Boltzman constant known as  $5.67 \times 10^{-8} [W/(\text{m}^2 \cdot \text{K}^4)]$ , and  $A_r/A_D$  is the of body surface fraction exposed to radiation equal to about 0.725 for a standing person. For low wind ( $V$  in m/s) conditions,  $hc$  is estimated from metabolic activity (see Appendix A for details).

The total respiratory heat loss is the sum of the evaporative respiratory loss ( $E_{res}$ ) (Fanger, 1972) and convective respiratory loss ( $C_{res}$ ). They are related to exercise intensity at a given environment (Kraning and Gonzalez, 1991):

$$E_{res} + C_{res} = 0.0023 \cdot M \cdot (44 - P_a) + 0.0014 \cdot M \cdot (34 - T_a) \quad [W/\text{m}^2] \quad (10)$$

where  $M$  is total metabolic activity in watts ( $W$ ) ;  $P_a$  is ambient vapor pressure; and  $T_a$  is air temperature.

Quantitatively, relative to respiratory heat loss, heat loss from the skin surface is much more significant. The maximum rate of evaporative heat loss ( $E_{max}$ ) from the skin surface is calculated based on the vapor pressure difference between skin surface and air:

$$E_{max} = (P_{sk} - P_a) / R_{p_{clt}} \quad [W/\text{m}^2] \quad (11)$$

where  $P_{sk}$  = saturated vapor pressure ( $T_{orr}$ ) of water at skin temperature;  $P_a$  = ambient vapor pressure; and  $R_{p_{clt}}$  = total vapor resistance of the clothing from skin to ambient.  $R_{p_{clt}}$  values used in this validation study report were measured by a sweating thermal manikin for the specific clothing ensembles used in this model.

**Sweat rates (SR):** The sweat rate (SR) for evaporative heat loss is modeled as being proportional to changes in mean body temperature ( $T_{mb}$ ) and skin temperature from set point values:

$$SR = 170 \cdot (T_{mb} - T_{mbset}) e^{-((T_{sk} - T_{skset})/10.7)} \quad g/(\text{h} \cdot \text{m}^2) \quad [g/\text{min}] \quad (12)$$

where the set point of  $T_{mb}$ ,  $T_{mbset} = 36.49^\circ\text{C}$  and  $T_{skset} = 33.7^\circ\text{C}$

Evaporative heat loss ( $E_{sk}$ ) is calculated from skin wettedness ( $w$ ), the fraction of the skin covered with sweat, and the maximum evaporation rate ( $E_{max}$ ) of 100% wet skin:

$E_{sk} = w \cdot E_{max}$ , where  $w = SR \cdot hfg / E_{max}$  and  $hfg$  is latent heat of evaporation ( $= .68 \text{ W} \cdot \text{h/g}$ ). If  $SR \cdot hfg > E_{max}$ ,  $w = 1$  and excess sweat drips off the skin. For the validation modeling, the maximum sweat rate was limited to  $667 \text{ g/(h} \cdot \text{m}^2)$ .

**PSI:** In addition to  $T_{cr}$ ,  $T_{sk}$ , and  $SR$ , the ICDA also calculates the Physiological Strain Index (PSI). PSI combines HR and  $T_{cr}$  values at any given time to provide a simple, concise and ordinal physiological strain scale between 0 and 10. PSI has been useful to evaluate heat strain in relation to various combinations of environmental (e.g., heat, humidity), operational (e.g., clothing, work rates) and biological (i.e., gender) conditions (Moran et al., 1988). The PSI was calculated as follows (13):

$$PSI = 5(T_{crt} - T_{cr0}) \cdot (39.5 - T_{cr0})^{-1} + 5 \cdot (HR_t - HR_0) \cdot (180 - HR_0)^{-1} \quad (13)$$

where  $T_{cr0}$  and  $HR_0$  are the initial  $T_{cr}$  and HR measurements at rest, and  $T_{crt}$  and  $HR_t$  are simultaneous measurements at a given time ( $t$ ).

The details of the physiological, thermodynamic and heat transfer functions of the ICDA are described further in APPENDIX A.

## VALIDATION DATA

The model validation was conducted using three laboratory heat studies. The investigators adhered to the policies for the protection of human volunteers as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 45 CFR Part 46. Test volunteers provided their informed consent prior to participation in the study and were free to withdraw from the study at any time.

Heat Study1 (HS1): Nine volunteers (8 males, 1 female; age:  $23 \pm 4$  [SD] yr; height  $174.2 \pm 5.2$  cm; weight:  $73.4 \pm 6.5$  kg; Body Mass Index (BMI):  $24.2 \pm 1.6$ ), wearing hot weather battle dress uniform (HWBDU) did intermittent exercise in a warm-humid environment ( $27^\circ\text{C}$ , 75%RH) for 170 minutes (Santee et al., 2005). The exercise routine consisted of walking on a level treadmill at  $1.34 \text{ ms}^{-1}$  for 30 minutes followed by 10 minutes of rest. These individuals were not heat acclimated prior to the study. The study conditions were relatively benign and no subjects were withdrawn due to pre-set physiological safety limits (Santee et al., 2005).  $T_{cr}$  was measured rectally and the skin surface temperature was averaged from 3 regions (back, arm, thigh) measured by heat flow discs (Santee et al., 2005). The average  $T_{sk}$  was calculated utilizing Burton's weighting method ( $0.5 \cdot T_{back} + 0.36 \cdot T_{thigh} + 0.14 \cdot T_{arm}$ ) (Santee et al., 2005).

Heat Study2 (HS2): Seven male Soldiers, wearing Army Physical Fitness Uniform (APFU) (i.e., T-shirt, shorts, socks, shoes), continuously walked on a treadmill with a 4% grade at  $1.56 \text{ m} \cdot \text{s}^{-1}$ . Metabolisms ranged from 420 – 620 watts in a hot dry ( $49^\circ\text{C}$ , 18%RH) condition (Montain et al., 2005). The maximum exercise duration was 100 minutes and subjects discontinued a test at a point of their voluntary exhaustion or  $T_{cr} > 39.0^\circ\text{C}$ . Subjects (age:  $22 \pm 5$  yr, height  $176 \pm 4$  cm; weight:  $71.1 \pm 9.3$  kg; BMI:  $22.9 \pm 2.4$ ) were un-acclimated on the 1<sup>st</sup> day of the study. The experiment was

repeated daily for 10 days (Montain et al., 2005). Only five volunteers participated on the 10<sup>th</sup> day. The data, collected on the 1<sup>st</sup> day (non-acclimated stage) and 10<sup>th</sup> day (acclimated stage), were utilized in this study. An ingestible telemetry temperature pill was utilized to measure  $T_{cr}$ . Skin temperatures were measured by thermocouples from four regions (i.e., chest, forearm, thigh, and calf) to calculate a mean weighted  $T_{sk}$  based on Ramanathan (1964) method described as  $0.3 \cdot (T_{chest} + T_{arm}) + 0.2 \cdot (T_{thigh} + T_{leg})$  (Montain et al., 2005).

Heat Study3 (HS3): Eight heat acclimated men (age:  $23 \pm 6$ yr; height:  $176 \pm 6$  cm; weight:  $76.0 \pm 15.4$  kg; BMI:  $24.4 \pm 4.3$ ), wearing chemical protective garments, walked on a treadmill with a 4-9 % grade at  $1.56$ - $1.65$  m•s<sup>-1</sup>. Metabolic effort averaged 450W and oxygen uptake was ~55% of  $Vo_{2max}$ . Participants walked until they voluntary withdrew from the study or  $T_{cr} > 39.5^{\circ}\text{C}$  (Latzka et al., 1998). Subjects were able to continue exercising for < 40 minutes at  $35^{\circ}\text{C}/45\%\text{RH}$ . Their physical characteristics (mean  $\pm$  SD) including age and anthropometry were:  $23 \pm 6$  yr, height:  $174.2 \pm 5.2$  cm; weight:  $73.4 \pm 6.5$  kg (Latzka et al., 1998).  $T_{cr}$  was measured rectally.  $T_{sk}$  was measured by thermocouples at four sites (i.e., forearm, chest, thigh, calf) and mean  $T_{sk}$  was calculated based on Ramanathan (1964) weighting method (Latzka et al., 2005).

Table 1 shows the summary of these three studies. Depending upon the study schemes, HR,  $T_{cr}$ , and  $T_{sk}$  were collected at different time intervals. Volunteers in all studies exercised without water replacement. Sweat rates were measured in HS1 and HS3, calculated by the difference in body weight and associated weights (i.e., clothing) between before and after work. If resting HR was not available, a default value of 70 bpm was used as the model input; otherwise actual HR of subjects who were resting or sitting at the beginning of the studies or the lowest HR during the studies was utilized as resting HR. In addition, if measured HR values during more active phases were missing, values interpolated over the time interval between existing data points were substituted. The HR summary in each study is displayed in APPENDIX B.



Table 1. The data summary used in this study

Study#	HS1	HS2	HS3
Ta (°C)	27	49	35
RH (%)	75	18	45
Acclimation Status	No	No-->Yes	Yes
Clothing	HWBDU	T-shirt & Shorts	Protective clothing
Activity (W)	277-350	412-628	343-552
Duration (min)	~170	<100	<40
n	9	7	8
Source	Santee et al., (2005)	Montain et al., (2005)	Latzka et al., (1998)

## STATISTICAL ANALYSIS

The predicted and observed  $T_{cr}$  and  $T_{sk}$  were compared using Root Mean Square Deviation (RMSD) in each individual. The RMSD was used to quantify the average difference between predicted and observed measurements across time (4).

The RMSD was calculated as follows:

$$RMSD = \sqrt{\frac{1}{n} \sum_{i=1}^n d_i^2} \quad (14)$$

where  $d_i$  = difference between observed and predicted at 1-min intervals; and  $n$  = the number of compared points.

In addition, Evaporative Sweat Rates (EvapSR) predicted by the ICDA model were compared with measured EvapSR in available studies, using a paired t-tests.

## RESULTS

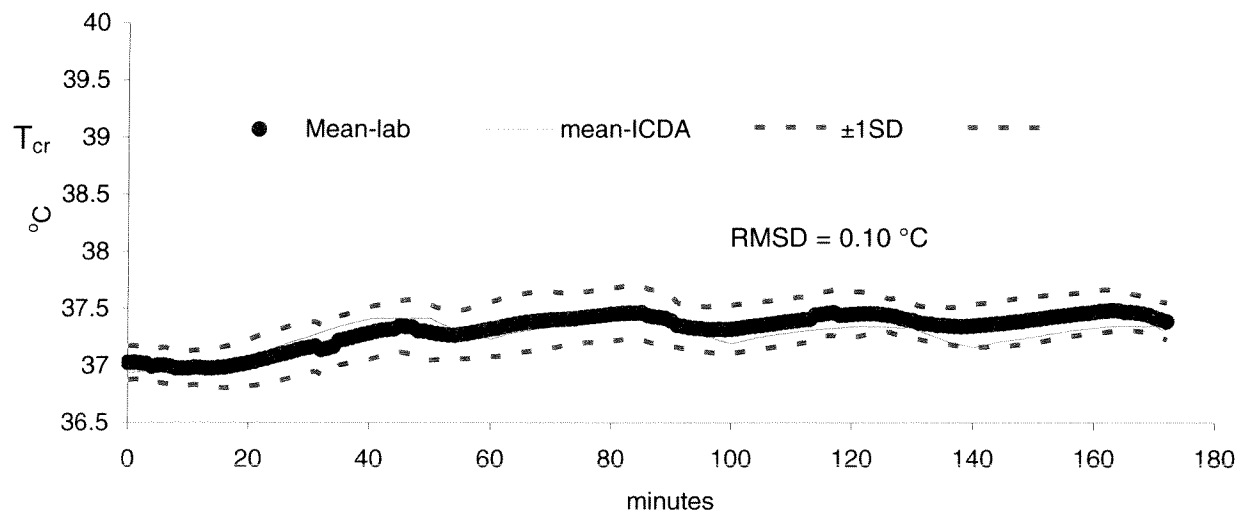
### CORE TEMPERATURE

Figure 3 (a-d) summarizes the comparisons of mean measured  $T_{cr}$  to the corresponding mean ICDA predictions. RMSD ranged between 0.11 and 0.50 °C for these studies. The model predictions were within one standard deviation of the mean measured values, when  $T_{cr}$  of the volunteers, wearing BDU and walking at 27°C /75% environmental conditions, were less than 38.0°C (e.g., Figure 3a). For the HS2 data, prediction errors were greater in non-acclimation subjects than in acclimated subjects at 49°C/18% (e.g., Figure 3b and 3c). Although  $T_{cr}$  in unacclimated individuals in HS2 quickly reached very high levels (> 39.0°C) (Figure 3b), after the 10-day heat acclimation process, the same individuals were able to maintain their  $T_{cr}$  at a lower level (~38.5°C) (Figure 3c). Initially, for heat acclimated Soldiers at 49°C/18%RH, the model predicted a rate of increase in  $T_{cr}$  greater than that measured; however, the model was more accurate toward the end of exercise (Figure 3c).

Errors of estimates were also larger when sample sizes, due to the voluntarily terminations, were smaller ( $n < 5$ ) (e.g., Figure 3b, 3d). However, ICDA predictions were reasonable for HS3 in which subjects, wearing protective garments and walking in a hot humid condition, increased their  $T_{cr} < 39.5^\circ\text{C}$ .

Figure 3 The summary comparisons between mean measured and predicted core temperature ( $T_{cr}$ ) from different heat studies.

a. Heat Study 1 (27°C, 75%; hot weather battle dress uniform; n=9)



b. Heat Study 2 (day1 – non acclimation state; 49°C, 18%; army physical fitness uniform; n≤7)

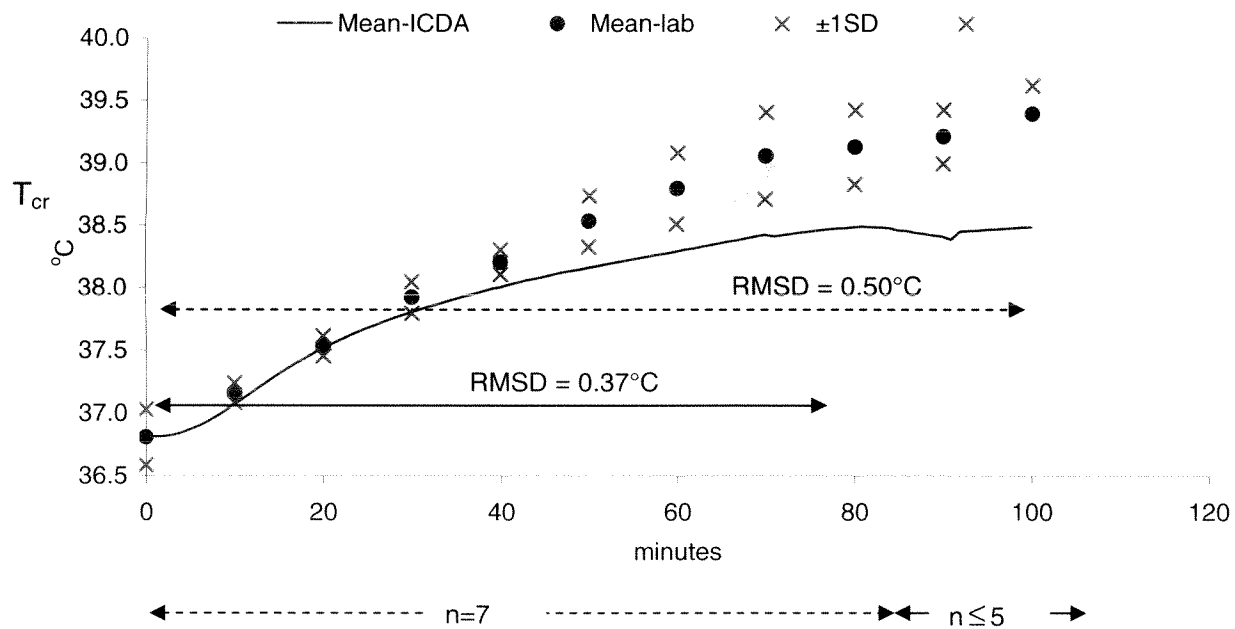
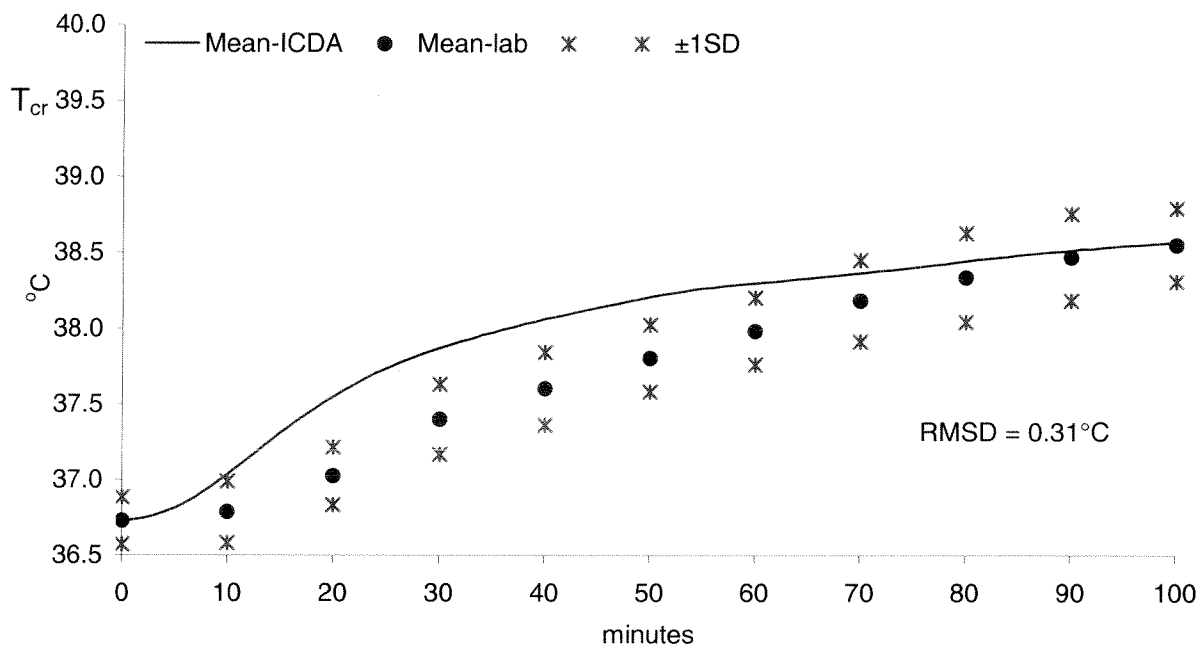
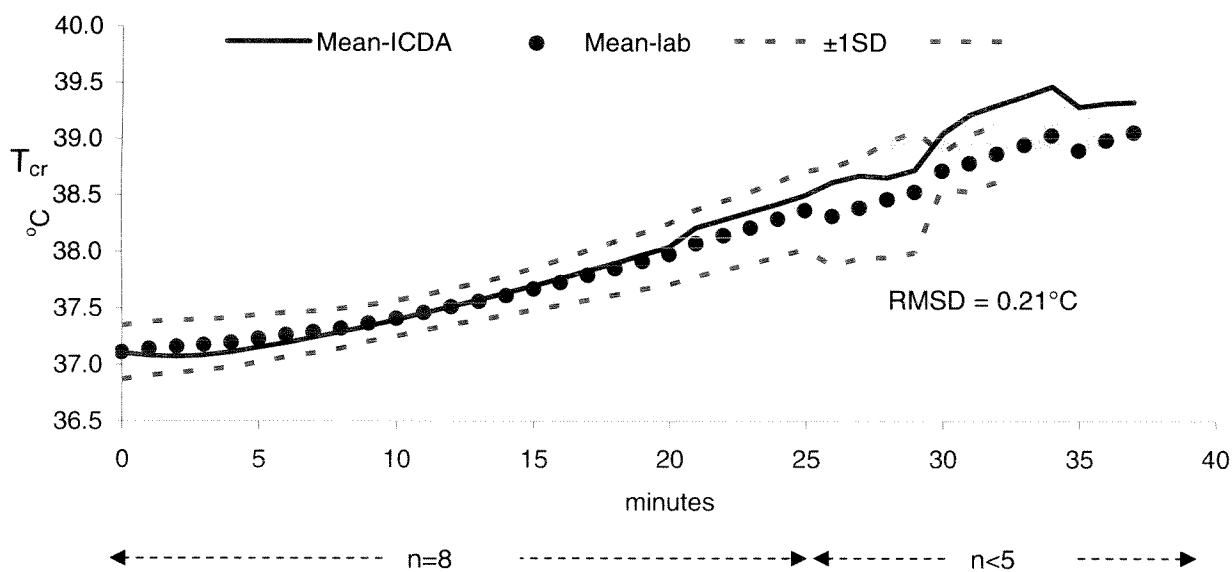


Figure 3 cont.

c. Heat Study 2 (day10 – heat acclimated state; 49°C, 18%; army physical fitness uniform; n=5)



d. Heat Study 3 (35°C, 45%; protective garment; n≤8)



## SKIN TEMPERATURE

The results of ICDA predictions for  $T_{sk}$  varied between the different studies.  $T_{sk}$  measurements on the 1<sup>st</sup> day in HS2 were not available. Overall, in comparison to the  $T_{cr}$  predictions, the model predictions of  $T_{sk}$  were less accurate. Figure 4 (a-c) shows the comparisons between measured  $T_{sk}$  and the model predictions for the three studies. In all studies, the model tended to over-predict the measured mean weighted  $T_{sk}$  (Figure 4a-c). In comparison to the other studies, predictions for HS3 (Figure 4c) showed better agreement with measured mean weighted  $T_{sk}$  (RMSD = 0.64°C). During HS3, volunteers wore protective clothing which limited evaporative heat transfer through clothing to the environment. In contrast, for HS1 and HS2 (Figure 4a, 4b), the model tended to over-predict measured mean weighted  $T_{sk}$  by about 1 °C or more.

Figure 4. Comparisons between mean measured and predicted skin temperature ( $T_{sk}$ ) for three heat studies.

a. Heat Study 1 (27°C, 75%; hot weather battle dress uniform; n=9)

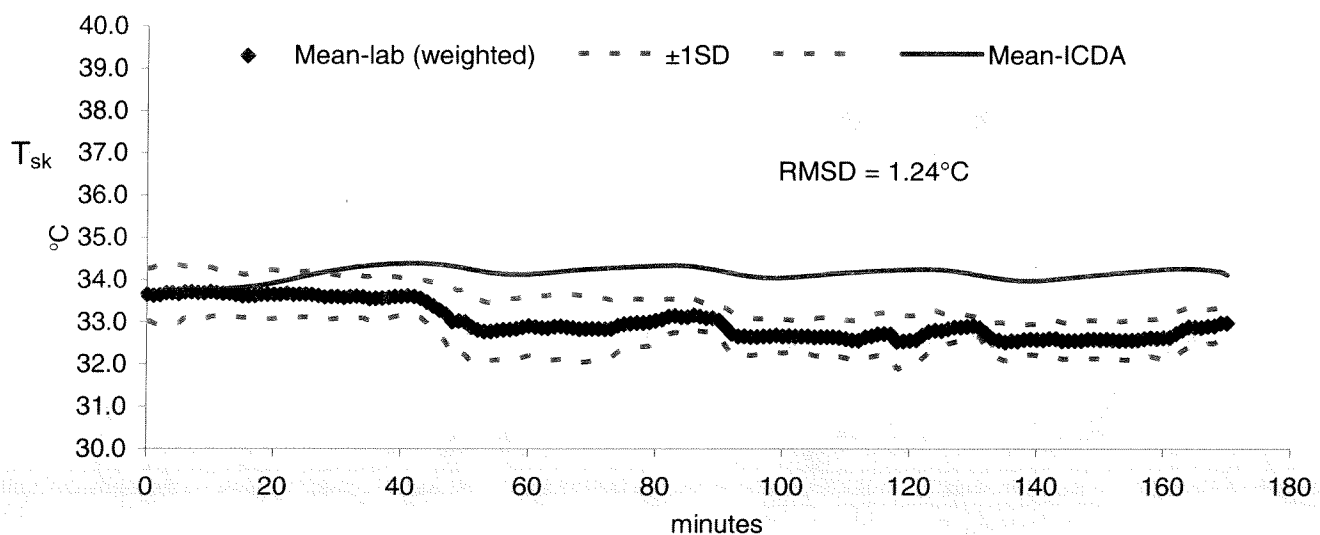
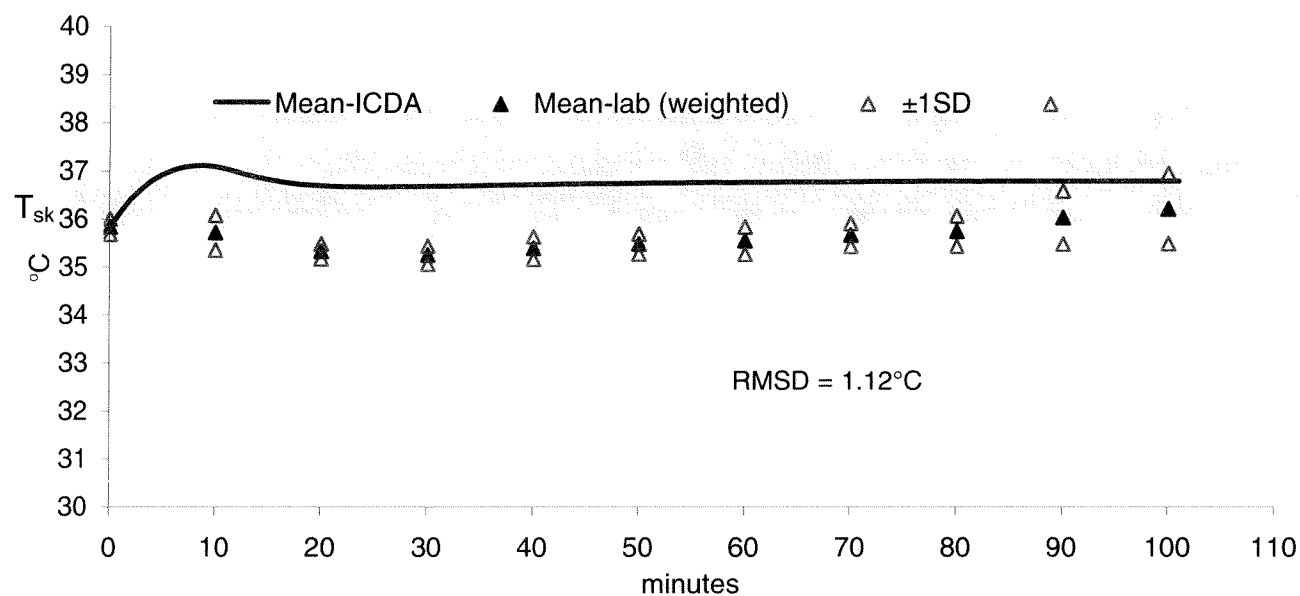
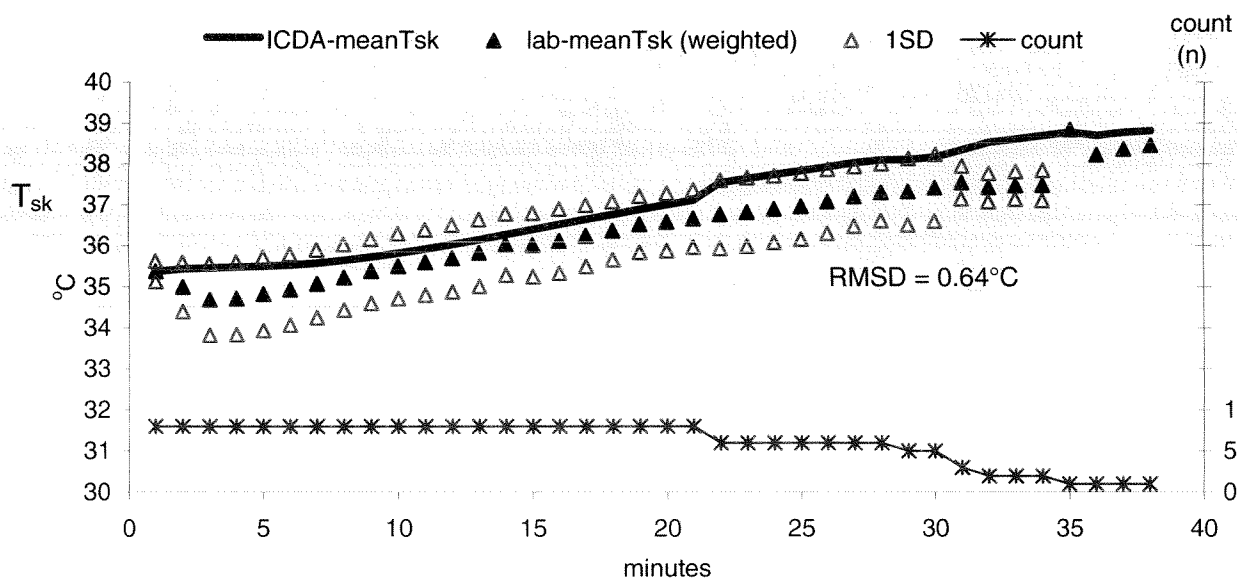


Figure 4 cont.

b. Heat Study 2 (day10 – heat acclimated state; 49°C,18%; army physical fitness uniform; n=5)



c. Heat Study 3 (35°C, 45%; protective garment; n≤8)



Accurate predictions for  $T_{sk}$  were problematic because measured  $T_{sk}$  varied by skin locations and between individuals. Figure 5a and Figure 5b are examples of regional  $T_{sk}$  collected from two volunteers in HS1. The first individual's thigh temperature ( $T_{thigh}$ ) (Figure 5a) agreed closely with predicted  $T_{sk}$ . However, the back ( $T_{back}$ ) and arm ( $T_{arm}$ ) temperatures were cooler after 30 minutes and the deviation between observed and predicted values for the arm increased with time. The second subject's  $T_{thigh}$  (Figure 5b) also agreed well with the predicted  $T_{sk}$ . The  $T_{back}$  was similar to  $T_{arm}$  until the  $T_{arm}$  sensor became detached during the final 140-160 minute.

Figure 5a. The distributions of measured skin temperatures by different regions and ICDA predictions in one individual (SN7) from HS1: Example 1.

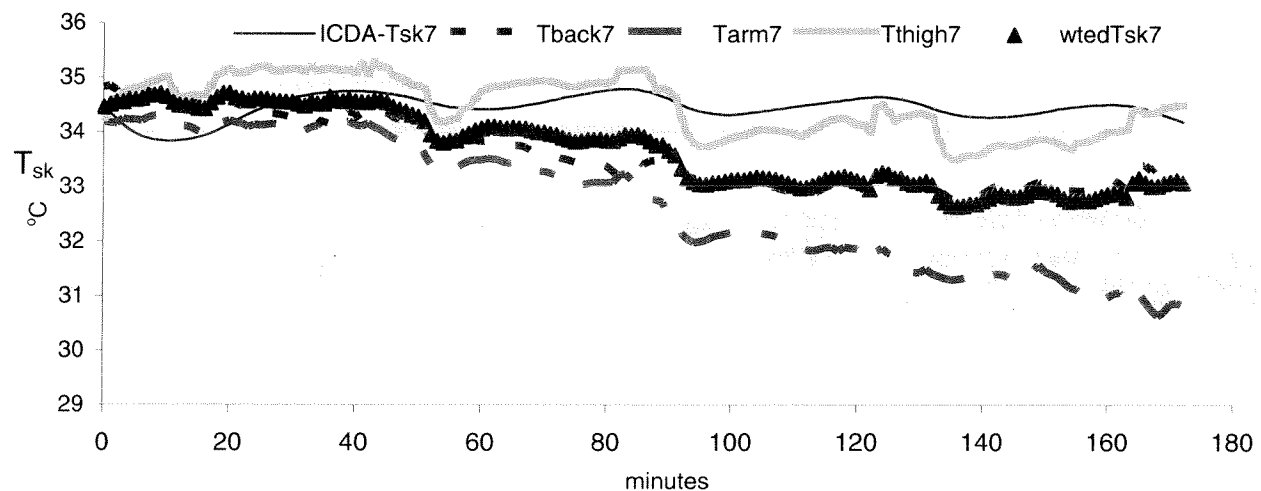
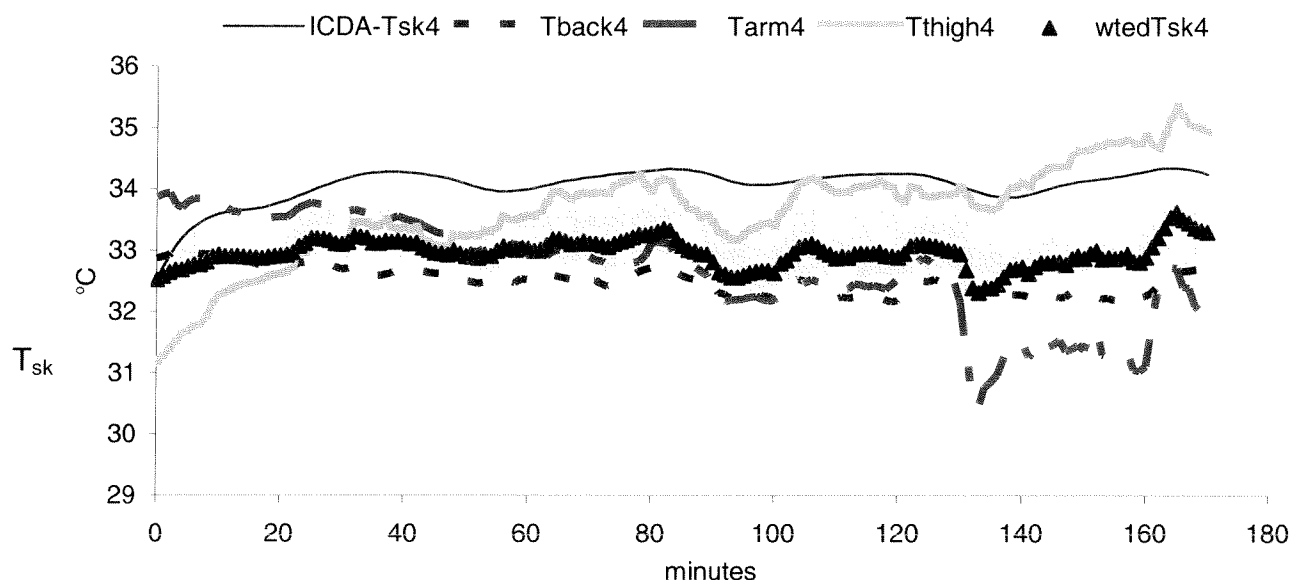


Figure 5 cont.

Figure 5b. The distributions of measured skin temperatures by different regions and ICDA predictions in one individual (SN4) from HS1: Example 2.



As opposed to the various  $T_{sk}$  responses in HS1 (Figure 5a, b), the responses of  $T_{sk}$  by region were relatively uniform in HS3 when subjects wore protective garments.

Figure 6a and 6b are examples of measured  $T_{sk}$  by region in HS3. Both individuals showed lower  $T_{calf}$  and higher  $T_{chest}$  than any other  $T_{sk}$  region. The maximum difference between  $T_{calf}$  and  $T_{chest}$  can be 4 $^{\circ}\text{C}$ ; however, the regional  $T_{sk}$  responses to heat stress during the experiment were very similar.



Figure 6a. The distributions of measured skin temperatures by different regions and ICDA predictions in one individual (SN2) from HS3: Example 1.

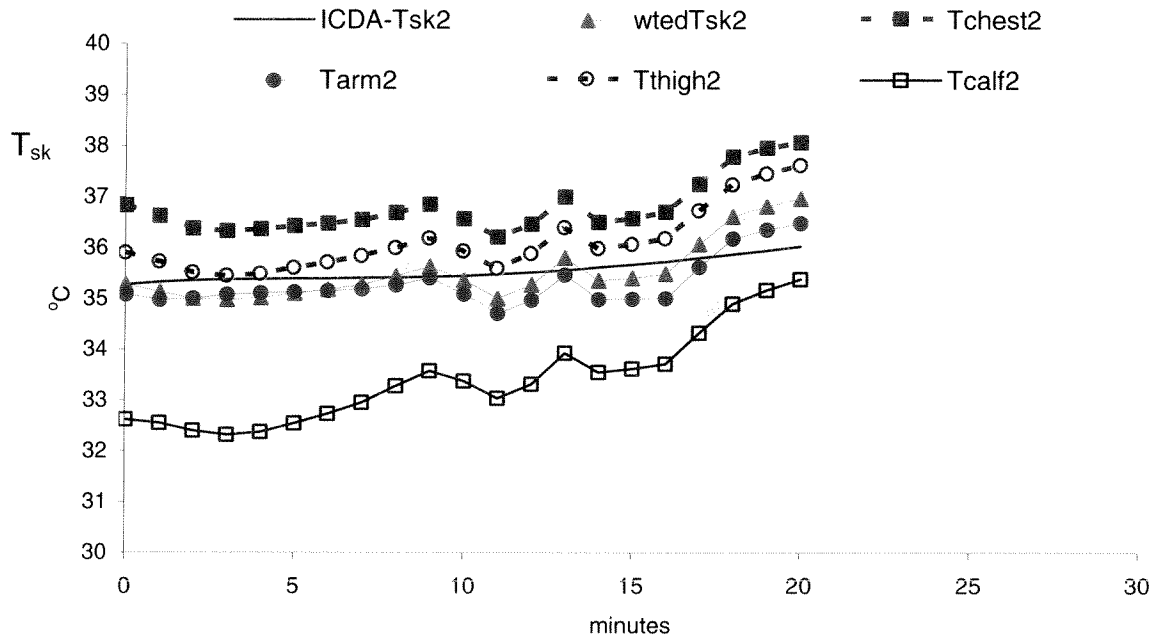
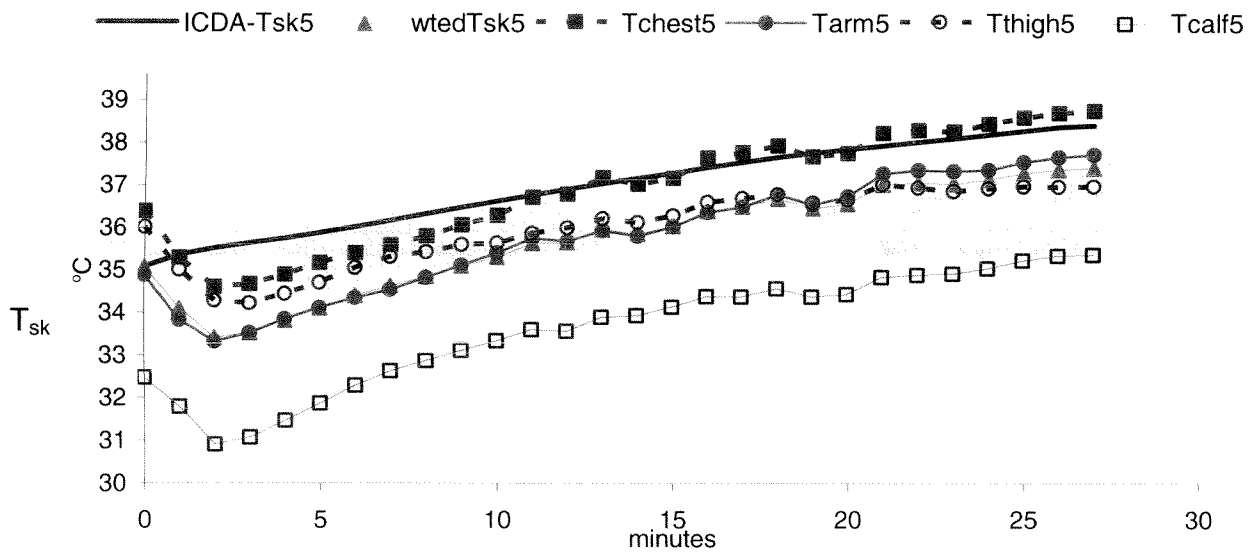


Figure 6b. The distributions of measured skin temperatures by different regions and ICDA predictions in one individual (SN5) from HS3: Example 2.



## SWEAT RATES

Measured sweat rate (SR) data from HS1 and HS3 were available. SR in both studies was calculated from difference in body weight and associated weights (e.g., clothing) before and after work. Summaries of individual comparisons between measured and ICDA predicted SR for HS1 and HS3 are summarized in Tables 2 and 3, respectively. For HS1, the grand mean of SR predicted by ICDA (3.23 g/min) was not statistically different from measured value of SR (3.13 g/min), using a paired t-test ( $p < 0.05$ ).

Table 2. Subject and group comparisons between measured Sweat Rates (SR) and predicted Sweat Rates (SR) for HS1.

Subject ID	lab SR (g/min)	ICDA SR (g/min)
1	3.71	2.39
2	3.44	4.03
3	1.57	2.38
4	3.17	4.35
5	3.17	2.70
6	3.97	3.06
7	2.64	2.90
8	2.77	3.37
9	3.71	3.92
MEAN	3.13	3.23
STDEV	0.73	0.73

In comparison to HS1, greater individual variability in SR was observed under the more strenuous heat conditions of HS3. ICDA SR predictions in HS3 varied by individual: similar SR predictions to measured SR ( $\Delta SR < 1.2$  g/min) were observed in three of eight individuals, while  $\Delta SR$  in the rest of subjects varied between 1.2 and 6.3 g/min. Using a paired t-test ( $p < 0.05$ ), mean values of measured and ICDA predicted SR were not statistically different for HS3. However, despite the favorable results for mean comparisons, individual variation for SR will need to be carefully considered for future predictions.

Table 3. Subject and group comparisons between measured Sweat Rates (SR) and predicted SR in HS3

Subject ID	lab SR (g/min)	ICDA SR (g/min)
1	8.83	3.01
2	9.07	3.64
3	7.19	6.69
4	5.28	10.16
5	12.66	12.46
6	11.95	13.84
7	14.33	8.04
8	12.55	11.41
MEAN	10.23	8.66
STDEV	3.12	4.01

## DISCUSSION

The ICDA model, derived from a minimum number of non-invasive inputs, was designed primarily for screening physiological responses of deployed Soldiers assigned for long-hour multiple tasks. The initial analysis of this simple model yielded promising results for predicting the thermal status of Soldiers during heat stress. The ICDA predictions for  $T_{cr}$  were within an acceptable range of  $\pm 1$ SD for non-heat acclimated volunteers when they were exposed to moderately stressful heat levels of  $27^{\circ}\text{C}/50\%\text{RH}$ . However, under more stressful conditions, the ICDA predictions were better for heat-acclimated individuals than non heat-acclimated individuals. Initially predictions showed  $T_{cr}$  increasing faster than measured  $T_{cr}$  in heat-acclimated Soldiers. However, by the end of exercise,  $T_{cr}$  predictions were more accurate. Under heat stress wearing protective garments, the ICDA predictions were close to measured  $T_{cr}$ , although error estimates were larger when sample sizes were smaller. An option to improve the simulation for more diversified populations (e.g., non-acclimated persons, different fitness, and civilian occupations) could be added if that is desirable.

Predicted values for  $T_{sk}$  were not as accurate as  $T_{cr}$  predictions. This may be due in part, to between and within individual variability, and differences between the regions represented by different  $T_{sk}$  measurement sites. This trend seems to be especially true when the environmental temperature was lower than measured  $T_{sk}$ . The variability between measurement sites was less when subjects wore protective garments or when working in a hot-humid environment. Before more modeling development, there should be agreement on the best, most representative sites for measurement of  $T_{sk}$  to accommodate variability among individuals, clothing, environment, and operations.

Two heat studies (HS1, HS3) allowed comparison of measured SR to the ICDA predicted SR. When the heat stress was less strenuous, the mean change ( $\Delta$ ) in SR was 0.1 g/min. When the heat stress was more strenuous, the  $\Delta$  in SR was greater. Although the mean predicted SR was not statistically different from the measured SR, prediction errors increased when individual variation in SR was increased. This may indicate that the estimate of M, based solely on HR, may not be adequate for accurate physiological predictions. For instance, predicted SR of two subjects in HS3 was lower than measured SR because of the high resting HR. As a result, a lower HR ratio was used to estimate lower M when  $T_a$  was constant. In these studies, resting HR was determined at rest or sitting at the beginning of the studies or lowest HR during the studies. It is possible that initial HRs were caused by anxiety, initial discomfort, or other physical or psychological factors, and were higher than under "true" neutral resting conditions. The affects of using a subjects' "true" resting HR on the calculated value of M need to be carefully considered.

Estimates of M from HR obtained using non-invasive methods are convenient for Soldiers who may be required to perform different tasks over many hours or even days. Normally, Soldiers deploying to regions known for extreme heat will be acclimatized during training for maximizing their performance and prevention from heat-related injuries. As the ICDA was primarily developed for heat acclimated Soldiers, predictions

of Soldiers' physiological status using the current version of ICDA will be more accurate for acclimated individuals. Although the present version of ICDA showed promising results with study data for some physiological parameters, further study, analysis, validation and improvements are recommended.

## CONCLUSIONS

The human simulation computer program ICDA has been validated to estimate  $T_{cr}$ ,  $T_{sk}$ , and SR using HR, environmental parameters and the Soldier's anthropological characteristics. The predictions were compared to measured values from three laboratory heat studies. Overall the simulation predictions of  $T_{cr}$  agreed well with the measured values for heat acclimatized Soldiers. The agreement for  $T_{sk}$  and SR was less accurate than  $T_{cr}$  and varied with clothing, environment, activity and individual differences, and should be evaluated further. Additional future experience with ICDA during field training situations will lead to further assessment, confidence, and possible improvements in application and hardware.

The ICDA real time physiological monitoring system was created for the narrow specialized application of trained heat acclimated Soldiers ready for deployment to a hot environment. However the system can be adapted for more variation in fitness, heat acclimation, body mass, age and other characteristics for application to more diverse groups of population and environment.

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## APPENDIX A

A documented listing of the basic ICDA model described in the introduction and used in the verification follows. It is slightly different from the real time simulator on the Soldier in that measured input is entered through a keyboard rather than directly from the sensor system. Also the specified measurement interval is not driven by a clock in this case so the measured values can be keyboard entered at operators pace. Following the program instructions an example of the output is given.

```
/* Origin: BBMD @ USARIEM
Authors: Berglund and Yokota
Date: 6/30/05
File: IC-DA-C-RT_Beta_steppedNonClockedInputs6_30_05
```

This simulates the real time thermal physiological responses( $T_c$ ,  $T_{sk}$ , waterLoss, skin wettedess,  $PS_{lc}$ ) from real time inputs of measured HR, environmental parameters( $T_a$ ,  $MRT$ ,  $RH$ ,  $V$ ) with constant personal properties( $ht$ ,  $wt$ ) and clothing.

The interval (in seconds) between measurements is adjustable. Enter 0 for the default interval of 60 seconds. In this program version the input interval is not controlled by a clock. Measurements values are entered through key board at these intervals. The measurement interval is also the model's integration interval.

Metabolism is expressed by dimensionless relative metabolism term ( $met$ ) where  $met = \text{actual metabolism} / \text{resting metabolism}$ .  $Met$  is estimated in this program from heart rate( $HR$ ) and air temperature( $T_a$ ). intrinsic clo is thermal resistance from skin to outer layer of clothing in clo units.  $MRT = \text{mean radiant temperature}$ .  $V = \text{air speed}$ . \*/

```
#include <assert.h>
#include <stdio.h>
#include <math.h>
#include <ctype.h>

#define TTSK 33.7 //°C
#define TTCR 36.8 //°C
#define TTBM 36.49 // TTBM=.9*TTCR+.1*TTSK =36.49
#define CSW 170. // g/(h m^2 °C)
#define CDIL 50. // CDIL 200 super athlete, 50 average person
#define CSTR .5 // 1/°C
#define SKBFN 6.3 // liters/(h m^2)
#define Skbfmax 90. // conservative could be higher for fit person
#define Skbfmin 2. //Liters/(h m^2)
#define CMIN 5.28 // w/(m^2 °C)
#define CB 1.163 // wh/(L °C)
#define WpMet 58.1 // w/(m^2*met)
#define LR 2.2 //Lewis relation

void OutputHeader();
double SatVapPres(double T);
double Clot(int code, double V); //total clo from skin to environment
double VRes(int code, double V); // total vapor resistance from skin to environment
double Convection(double met, double V); //convective heat transfer coefficient
double Respiration(double Rm, double Ta, double Pa, double* Wres); //respiratory heat loss
```



```

double SkinBloodFlow(double Tc, double Tsk);
double DuBoisSkinArea(double Wt, double Ht); //surface area of body
double MetT(double HR,double HRrest,double T);
double Alpha(double Skbf); // fraction of body that is skin
double Sweat(double Tc, double Tsk,double alpha);
double Core(double Tc,double Tsk,double met,double Res,double* hfcsk, double skbf,double* Rm);
double Skin(double wet,double Dry,double Emax,double* hfcsk);
double MoranPSI(double Tc,double Tco,double HR,double HRrest); //heat stress index

```

```

int main (void){
    int step, HrTimeStep,code;double Ta,Tanew,MRT,MRTnew,RH,RHnew,Pa,Psk,Tcl,To,V,Vkm,Vnew;
    double hc,he,hr,met,Ht,Wt,Adu,Wres, drip,DT,DTs,ExTime;
    double wet,Tsk,Tsko,Tc,Tco,Rm,clo,FACL,Dry,Fpcl,PSlc;
    double Emax,Esk,Edif,Res,Skbf,HRrest,HR,HRnew,alpha,Regsw,Ersw;
    double heatFlowCoreToSkin,HSCR,HSSK,TCCR,TCSK,Rcl,Rbound,Rclt,Rpcl, Rpbound,Rpclt;
    double time,TIM,Duration,DurationM,CumulativeWaterLossPsqm;
    doubleCumulativeWaterLoss,CWLL,RateOfTotalWaterLossPsqm, RateOfTotalWaterLoss,Wdif;

```

```

TIM=0; step=0; time =0; HR=0; HRrest=0; DTs=0;ExTime=0; HrTimeStep=0;

```

```

printf("Enter interval between measurements in seconds(0 for default of 60 seconds):DTs ");
scanf("%lf",&DTs);
if (DTs<=0)
    DTs=60;
DT=DTs/(60*60); //DT in hrs
printf("Enter intrinsic clo or -1 if unknown: clo ");
scanf("%lf",&clo);
code=0;
if (clo<0){
    printf(" Codes of manikin tested clothing types available for simulation: \n 1 HWBDU \n 2
    APFU(SHTS+T) \n 3 Protective Garment(MOPP4) \n Enter Code: code ");
    scanf ("%d",&code); }
printf("Enter subject's weight(kg),height(m)(or 0's if unknown): Wt Ht ");/* inserts default values of
70kg,1.72m */
scanf("%lf%lf",&Wt,&Ht);
if (Wt<=0)
    Wt=72.8;
if (Ht<=0)
    Ht=1.72;
printf("Enter subject's resting HR)(or 0's if unknown):HRrest ");/* inserts default values of 70 if HRrest
are zero */
scanf("%lf",&HRrest);
if (HRrest<=0)
    HRrest=70;
Adu=DuBoisSkinArea(Wt,Ht); //m^2
printf("Enter initial physiology (or 0's if unknown): Tsk Tc ");/* inserts default values if Tsk,Tcr are
zero's */
scanf("%lf%lf",&Tsk,&Tc);
if (Tsk <=0){
    Tsk=33; Tsko=Tsk; }
else
    Tsko=Tsk;
if (Tc <=0){
    Tc=36.9; Tco=Tc; }
else
    Tco=Tc;

```

```

wet=.06;
printf("Enter duration(min): "); //may wish to delete duration for real applications

scanf("%lf",&DurationM);
Duration=DurationM/60.; //hr
printf("Enter HR Ta(C) MRT(C) RH(percent) V(km/h) : ");
scanf("%lf%lf%lf%lf%lf",&HR,&Ta,&MRT,&RH,&Vkm);
V =Vkm*1000/(60*60); // convert km/h to m/s
met=MetT(HR,HRrest,Ta); //from Berglund 30th ACEMB,1977
OutputHeader();

Pa=RH*SatVapPres(Ta)/100; // vapor press Torr
Sbfb=SkinBloodFlow(Tc,Tsk); //Liters/(h m^2)
alpha=Alpha(Sbfb); //skin fraction of body =Wtsk/Wt
Regsw=Sweat(Tc,Tsk,alpha); // g/(h m^2)
CumulativeWaterLossPsqm=0;
CumulativeWaterLoss=0;
drip=0; CWLL=0;
hc = Convection(met,V); // convection
hr=4.5; //radiation watts/(m^2 K)
To=(hc*Ta + hr*MRT)/(hc+hr);
if (code==0) {
    FACL=1.0+.2*clo; // surface area of clothing relative to Adu
    Rcl=.155*clo; // clothing thermal resistance m^2 C/watts
    Rbound=1/((hr+hc)*FACL); // boundary layer thermal resistance m^2 C/watts
    Rclt=Rcl+Rbound;
    Rpcl=.153181*clo; }
else {
    FACL=1.2; //guess with clo=1
    Rclt=.155*Cloth(code,V);
    Rbound=1/((hr+hc)*FACL); // boundary layer thermal resistance m^2 C/watts
    Rcl=Rclt-Rbound;
    clo=Rcl/.155; //estimate of uniform's intrinsic clo
    FACL=1+.2*clo; }
Dry=(Tsk-To)/(Rclt);
Tcl = To +Dry/(FACL*(hr+hc));

PSIc=MoranPSI( Tc,Tco, HR, HRrest);
printf("%5.1f %5.1f %5.1f %4.0f %5.2f %5.2f %5.2f %5.2f %5.2f %4.0f %5.3f %5.2f \n
",ExTime,Ta,MRT,RH,Vkm,Tc,Tsk,met,Regsw/60*Adu,wet,HR,CWLL,PSIc);
time+=Duration;
while (TIM<=time) { // thermo-physiology loop
// dry and evaporative heat transfer
Sbfb=SkinBloodFlow(Tc,Tsk); //Liters/(h m^2)
Psk=SatVapPres(Tsk); // vapor press Torr (mmHg)
Rm= WpMet*met; // watts/(m^2)
hc = Convection(met,V); // convection */
he=2.2*hc; // evaporation watts/(m^2 Torr)
hr=4*.725*(5.67E-08)*pow(((Tcl+To)/2+273),3); // corrected hr
To=(hc*Ta + hr*MRT)/(hc+hr);
if (code==0) {
    Fpcl=1/(1+.153181*he*FACL*clo); //Berglund 1981, for IL=.45
    Rpbound=1/(he*FACL);
    Rpclt=Rpcl+Rpbound;
    Rbound=1/((hc+hr)*FACL);
    Rclt=Rbound+Rcl; }

```

```

else {
    Rpclt=VRes(code,V); }
Emax=(Psk-Pa)/Rpclt;
Dry=(Tsk-To)/(Rclt);
Tcl = To +Dry/(FACL*(hr+hc));

// Thermal Physiology
Res = Respiration(Rm,Ta,Pa,&Wres);
alpha=Alpha(Skbf);
Regsw=Sweat(Tc,Tsk,alpha);      // g/(h m^2)
Ersw=.68*Regsw;                  // watts/m^2
Edif = (1-wet)*.06*Emax;         // diffusion through dry skin
Wdif=Edif/.68;                   // g/(h m^2)
Esk=(Wdif+Regsw)*.68;            // energy lost by evaporation from and diffusion through skin.
wet=Esk/Emax;
if (wet>=1){
    wet=1;
    drip=(Wdif+Regsw)-(Emax/.68); } // wasted sweat dripping from skin g/(hm^2)
else {
    drip=0; }
Esk=(.06+.94*wet)*Emax;
RateOfTotalWaterLossPsqm=Regsw+Wres+Wdif;      // g/(h m^2)
RateOfTotalWaterLoss=RateOfTotalWaterLossPsqm*Adu; //g/h m^2)
CumulativeWaterLossPsqm=CumulativeWaterLossPsqm+RateOfTotalWaterLossPsqm*DT;
CumulativeWaterLoss=CumulativeWaterLoss+RateOfTotalWaterLoss*DT;
CWLL=CumulativeWaterLoss/1000;                 //Liters
PSIc=MoranPSI( Tc,Tco, HR, HRrest);
HSCR = Core(Tc,Tsk,met,Res,&heatFlowCoreToSkin,Skbf,&Rm);
HSSK = Skin(wet,Dry,Emax,&heatFlowCoreToSkin);

/* thermal capacity */
TCCR=.97*(1-alpha)*Wt;
TCSK=.97*alpha*Wt;

/* stepwise integration */
Tc +=HSCR*Adu/TCCR*DT;
Tsk +=HSSK*Adu/TCSK*DT;
TIM +=DT;
ExTime+=DT*60; //min
printf("Enter HR Ta MRT RH V or 0 for any unchanged parameter: ");
scanf("%lf%lf%lf%lf%lf",&HRnew,&Tanew,&MRTnew,&RHnew,&Vnew);
if (HRnew>0)
    HR=HRnew;
if (Tanew>0)
    Ta=Tanew;
if (MRTnew>0)
    MRT=MRTnew;
if (RHnew>0)
    RH=RHnew;
if (Vnew>0) {
    Vkm=Vnew;      //km/h
    V=Vkm*1000/(60*60); } //m/s
met=MetT(HR,HRrest,Ta);
printf("%5.0f %5.1f %5.1f %4.0f %5.2f %5.2f %5.2f %5.2f %5.2f %4.0f %5.3f %5.2f\n",
    ExTime,Ta,MRT,RH,Vkm,Tc,Tsk,met,Regsw/60*Adu,wet,HR,CWLL,PSIc);
}

```

```

    return 0 ;
}

void OutputHeader() {
    printf("\nmin  Ta  Tr  RH  V  Tc  Tsk  met  sw  wet  HR  CWLoss  PStc\n");
    printf("      C  C      km/h  C  C      g/min  bpm  L\n");
}

double SatVapPres(double T) {
    double Pst;
    Pst = exp(18.6686-(4030.183/(T+235.))); //mmhg
    return Pst;
}

double Clot(int code, double V) {
    double A1=0,B=0;
    switch (code) {
        case 1: //HWBDU
            A1=1.08; B=-0.27; break;
        case 2: //APFU(SHTS+T)
            A1=0.51; B=-0.39; break;
        case 3: //Protective Garment(MOPP4)
            A1=1.7; B=-0.16; break;
        default:printf("Illegal clothing code,must be an integer between 1 and 3 ");break; }
    return A1*pow(V,B);
}

double VRes(int code, double V) {
    double Ai1=0,Bi=0;
    switch (code) {
        case 1: //HWBDU
            Ai1=0.47; Bi=0.41; break;
        case 2: //APFU(SHTS+T)
            Ai1=1.41; Bi=0.58; break;
        case 3: //Protective Garment(MOPP4)
            Ai1=0.17; Bi=0.31; break;
        default:printf("Illegal clothing code,must be an integer between 1 and 3 "); break; }
    return 0.155/(LR* Ai1*pow(V,Bi));
}

double Convection(double met,double V) {
    double CHCA, CHCV, CHCmin, hc; CHCmin = 3.0;
    if (met>=1.1) {
        CHCA = 5.66*pow((met - 0.85),0.39); // hc due to activity
    } else {
        CHCA = 5.66*pow((1. - 0.85),0.39); } // hc due to activity
    }
    CHCV = 8.6*pow(V,0.53); // hc due to air speed V in m/s */
    if (CHCV >= CHCmin) ;
    else
        (CHCV = CHCmin);
    if (CHCV >= CHCA)
        hc = CHCV;
    else
        hc = CHCA;
}

```

```

    return hc;
}

double Respiration(double Rm, double Ta, double Pa, double Wres){
    double Res, Eres, Cres;
    Eres = 0.0023*Rm*(44.-Pa);           // watts/m2
    Cres = 0.0014*Rm*(34.-Ta);           // watts/m2
    *Wres=Eres/.68;                       // g/(h m^2) */
    Res = Eres + Cres;
    return Res;
}

double DuBoisSkinArea(double Wt, double Ht) {
    double Adu; /* m^2 */
    Adu=0.202*pow(Wt,0.425)*pow(Ht,0.725); // Wt weight in kg, Ht height in m.
    return Adu;
}

double MetT(double HR, double HRrest, double T) { // Berglund, 30th ACEMB 1977
    double met, HRratio; /* applicable: 20<=T<=40, 0.6clo, v~=1.25m/s, 1.2<+HRratio<=2.1, Tdp<=20C */
    HRratio=HR/HRrest;
    if (HRratio>=1.2) {
        if (T>=20)
            met=0.68+4.69*(HRratio -1)- 0.052*(HRratio-1)*(T-20);
        else
            met=0.68+4.69*(HRratio -1); }
    else {
        met=HRratio; }
    return met;
}

double Alpha(double Skbf) {
    double alpha;
    alpha=0.04177+.74518/(Skbf+0.585417);
    return alpha;
}

double Sweat(double Tc, double Tsk, double alpha) {
    double regsw, Tmb;
    regsw=0;
    Tmb=(1-alpha)*Tc + alpha*Tsk;
    if ((Tmb>TTBM)&&(Tsk>TTSK))
        regsw=CSW*(Tmb-TTBM)*exp((Tsk-TTSK)/10.7);
    else if ((Tmb>TTBM)&&(Tsk<=TTSK))
        regsw=CSW*(Tmb-TTBM);
    if (regsw>667) // max sweat rate limit
        regsw=667; // regsw_max=667g/(h m^2)=11.1g/(min m^2)!=20g/(min m^2)
    return regsw; //g/(h m^2)
}

double SkinBloodFlow(double Tc, double Tsk) {
    double Colds=0;
    double Skbf, WarmC=0;
    if (Tsk<TTSK)
        Colds=TTSK-Tsk;
    if (Tc>TTCR)

```

```

        WarmC=Tc-TTCR;
        Skbf=(SKBFN+CDIL*WarmC)/(1+CSTR*Colds);           // Liters/(h m^2)
        if (Skbf>Skbfmax)
            Skbf= Skbfmax;
        if (Skbf<Skbfmin)
            Skbf= Skbfmin;
        return Skbf;                                     // L/(h m^2)
    }

double Core(double Tc,double Tsk,double met,double Res,double*heatFlowCoreToSkin, double Skbf,
double*Rm) {
    double Rmet,Hfcrsk,HSCR;
    Hfcrsk=(CMIN+CB*Skbf)*(Tc-Tsk);                     // watts/m^2
    Rmet = 58.2*met ;                                   // metabolic heat produced watts/m^2.
    HSCR=Rmet-Hfcrsk-Res;                                // rate of heat storage in core  watts/m^2
    *heatFlowCoreToSkin=Hfcrsk;
    *Rm=Rmet;
    return HSCR;
}

double Skin(double wet,double Dry,double Emax,double*heatFlowCoreToSkin ) {
    double Esw,Ediff,Esk,HSSK;
    Esw=wet*Emax;
    Ediff=.06*(1-wet)*Emax;
    Esk=Esw+Ediff;
    HSSK=*heatFlowCoreToSkin-Dry-Esk;                   // rate of heat storage in skin watts/m^2
    return HSSK;
}

double MoranPSI(double Tc,double Tco,double HR, double HRrest){
    double PSI;
    PSI=5*((Tc-Tco)/(39.5-Tco)+(HR-HRrest)/(180-HRrest));
    return PSI;
}
}
/* This is the End */

```

/\* output is pasted below

Enter interval between measurements in seconds(0 for default of 60 seconds):DTs 0

Enter intrinsic clo or -1 if unknown: clo -1

Codes of manikin tested clothing types available for simulation:

- 1 HWBDU
- 2 APFU(SHTS+T)
- 3 Protective Garment(MOPP4)

Enter Code: code 2

Enter subject's weight(kg),height(m)(or 0's if unknown): Wt Ht 0 0

Enter subject's resting HR)(or 0's if unknown):HRrest 0

Enter initial physiology (or 0's if unknown): Tsk Tc 0 0

Enter duration(min): 10

Enter HR Ta(C) MRT(C) RH(percent) V(km/h) : 75 27 27 75 4

min	Ta	Tr	RH	V	Tc	Tsk	met	sw	wet	HR	CWLoss	PSIc
	C	C		km/h	C	C		g/min		bpm	L	
0.0	27.0	27.0	75	4.00	36.90	33.00	1.07	0.00	0.06	75	0.000	0.23

Enter HR Ta MRT RH V or 0 for any unchanged parameter: 90 0 0 0 0

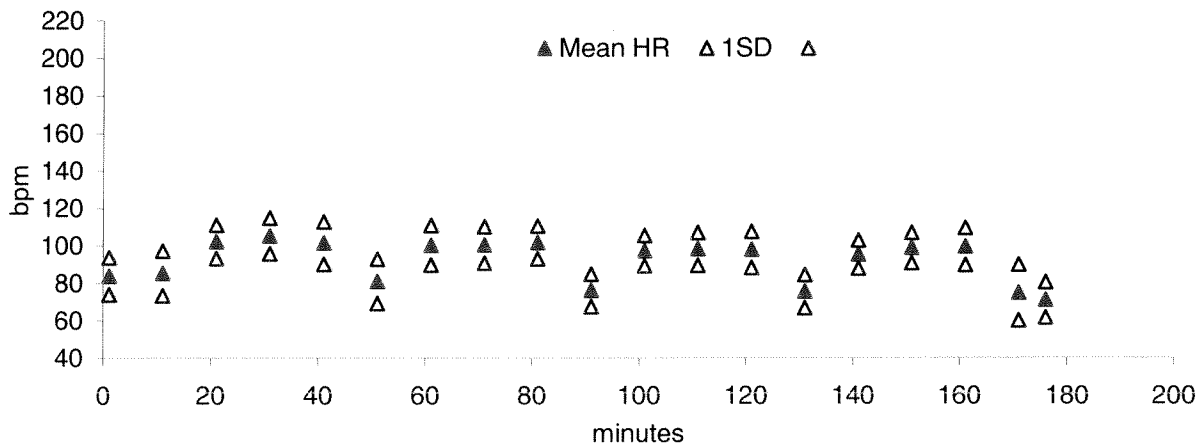
1 27.0 27.0 75 4.00 36.90 32.78 1.92 0.00 0.06 90 0.001 0.23  
 Enter HR Ta MRT RH V or 0 for any unchanged parameter: 109 0 0 0 0  
 2 27.0 27.0 75 4.00 36.92 32.58 3.09 0.00 0.06 109 0.002 0.91  
 Enter HR Ta MRT RH V or 0 for any unchanged parameter: 107 0 0 0 0  
 3 27.0 27.0 75 4.00 36.98 32.41 2.97 0.00 0.06 107 0.004 1.82  
 Enter HR Ta MRT RH V or 0 for any unchanged parameter: 108 0 0 0 0  
 4 27.0 27.0 75 4.00 37.02 32.27 3.03 0.00 0.06 108 0.005 1.83  
 Enter HR Ta MRT RH V or 0 for any unchanged parameter: 0 0 0 0 0  
 5 27.0 27.0 75 4.00 37.06 32.16 3.03 0.00 0.06 108 0.006 1.96  
 Enter HR Ta MRT RH V or 0 for any unchanged parameter: 0 0 0 0 0  
 6 27.0 27.0 75 4.00 37.10 32.06 3.03 0.26 0.07 108 0.008 2.04  
 Enter HR Ta MRT RH V or 0 for any unchanged parameter: 0 20 20 0 0  
 7 20.0 20.0 75 4.00 37.13 31.98 3.23 0.48 0.09 108 0.010 2.11  
 Enter HR Ta MRT RH V or 0 for any unchanged parameter: 0 0 0 0 0  
 8 20.0 20.0 75 4.00 37.17 31.51 3.23 0.68 0.10 108 0.012 2.17  
 Enter HR Ta MRT RH V or 0 for any unchanged parameter: 0 0 0 0 0  
 9 20.0 20.0 75 4.00 37.20 31.12 3.23 0.52 0.09 108 0.013 2.24  
 Enter HR Ta MRT RH V or 0 for any unchanged parameter: 0 0 0 0 0  
 10 20.0 20.0 75 4.00 37.23 30.81 3.23 0.43 0.09 108 0.015 2.30  
 Press any key to continue

\*/

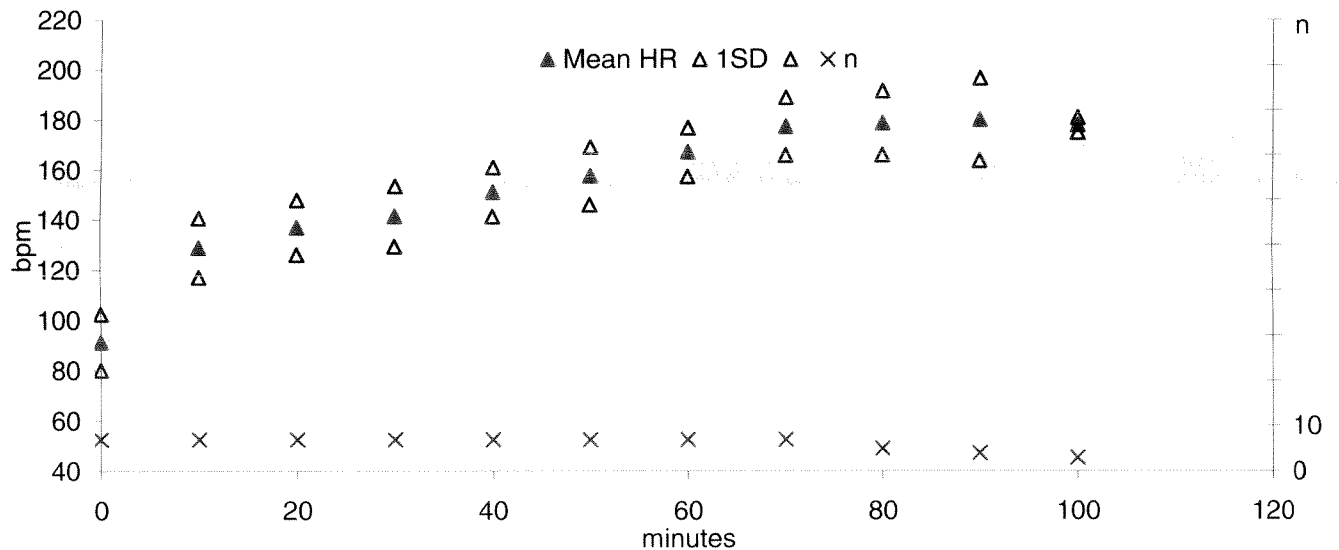
## APPENDIX B

The mean HR and  $\pm 1SD$  from each study are displayed.

### a. Heat Study 1 (27°C, 75%; HWBDU; n=9)



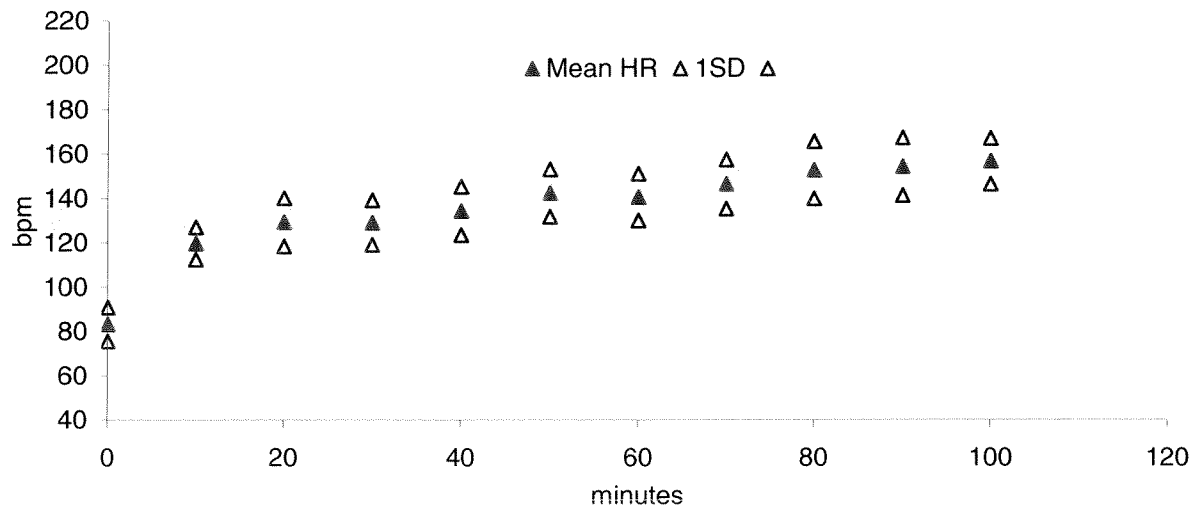
### b. Heat Study 2 (day1 – non acclimation state; 49°C, 18%; APFU; n≤7)





# APPENDIX B cont.

## c. Heat Study 2 (day2 – acclimation state; 49°C, 18%; APFU; n=5)



## d. Heat Study 3 (35°C, 45%; protective garment; n≤8)

